

Strömgren photometry and spectroscopy of the δ Scuti stars 7 Aql and 8 Aql

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Abstract

Photometric ($ubvy - \beta$) and spectroscopic observations of the δ Scuti variables 7 Aql and 8 Aql are described. The Strömgren standard indices and physical parameters of both stars are derived. Spectral types of F0V and F2III have been assigned to 7 Aql and 8 Aql respectively considering the results from both spectroscopy and photometry. Differential $ubvy$ light curves were also analyzed. A attempt of multicolour mode identification is carried out.

Keywords: stars: δ Sct – techniques: photometric, spectroscopic – stars:oscillations – stars: individual: 7 Aql, 8 Aql, HD 174046, HD 174625

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1. Introduction

7 Aql (HD 174532, SAO 142696, HIP 92501) was discovered to be a pulsating star of δ Scuti type by Garrido et al. (2002) in a search of new variables in preparation for the COROT mission. Its multiperiodic nature was established by Fox Machado et al. (2007) who detected six oscillation frequencies. 8 Aql (HD 174589, SAO 142706, HIP 92524) was reported as a new multiperiodic δ Scuti variable with three pulsation frequencies by Fox Machado et al. (2007). The dominant modes detected by Fox Machado et al. (2007) were confirmed by Fox Machado et al. (2008a) by using CCD photometry. Both stars represent interest for asteroseismology since they are slightly evolved, and hence located in the HR diagram in the ambiguous transition phase between core hydrogen burning and thick shell hydrogen burning. This phase is sensitive to the treatment of the core overshooting processes. Moreover, 7 Aql has been selected as a secondary target of the COROT seismology program (Uytterhoeven et al., 2009). The COROT space mission (Baglin et al., 2006), successfully launched in December 2006, is providing a huge number of detected oscillation frequencies in individual δ Scuti stars (Poretti et al., 2009; García Hernández et al., 2009). In order to fully exploit the asteroseismic data by using stellar evolutionary models, accurate stellar physical parameters are needed. For 7 Aql no $ubvy - \beta$ indices have been reported to date. On the contrary, a number of Strömgren indices [$(b - y)$, m_1 , c_1 , H_β] have been reported for 8 Aql, but based on a few measurements. Concerning the spectral classification of the stars, the reported types are not unique in the literature. Namely, the Michigan Catalogue of HD stars, Vol.5 (Houk+, 1999) reports F0V and A9IV for 8 Aql and 7 Aql respectively. Whereas, the SAO Star Catalog J2000 (SAO Staff

1966; USNO, ADC 1990) lists A2 for 7 Aql and A3 for 8 Aql. The Bright Star Catalogue, 5th Revised Ed. (Hoffleit+, 1991) gives F2III for 8 Aql. These classifications are based mainly upon photographic spectra which are less accurate than those obtained with modern equipments. The aim of this paper is to present more precise information about 7 Aql and 8 Aql by using both Strömgren photometry and spectroscopy. Furthermore, the differential time series in the Strömgren bands $ubvy$ are also analyzed.

2. Observations and data reduction

2.1. Photometric observations

The observations were secured in 2007 on the nights of June 21, 22, 23, 28, 30 and July 07 and 08 at the Observatorio Astronómico Nacional-San Pedro Mártir (OAN-SPM), Baja California, Mexico. The 1.5-m telescope with the six-channel Strömgren spectrophotometer was implemented. The observing routine consisted of five 10 s of integration of the star from which five 10 s of integration of the sky was subtracted. Two constant comparison stars were observed as well, namely HD 174046 and HD 174625. Along with 7 Aql and 8 Aql also observed was the δ Scuti variables HD 170699. The results for this particular objects will be given elsewhere (Álvarez et al., 2009).

A set of standard stars was also observed each night to transform instrumental observations onto the standard system and to correct for atmospheric extinction. The instrumental magnitudes ($_{inst}$) and colours, once corrected from atmospheric extinction, were transformed to the standard system ($_{std}$) through the well known transformation relations given by Strömgren (1966) :

$$V_{std} = A + y_{inst} + B(b - y)_{inst}$$

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$$(b - y)_{\text{std}} = C + D(b - y)_{\text{inst}}$$

$$m_{1,\text{std}} = E + Fm_{1,\text{inst}} + G(b - y)_{\text{inst}}$$

$$c_{1,\text{std}} = H + Ic_{1,\text{inst}} + J(b - y)_{\text{inst}}$$

$$H_{\beta,\text{std}} = K + LH_{\beta,\text{inst}}$$

where V is the magnitude in the Johnson system, and the m_1 and the c_1 indices are defined in the standard way: $m_1 \equiv (u - v) - (v - b)$ and $c_1 \equiv (v - b) - (b - y)$. Applying the above equations to the standard stars, an estimation of the mean errors for the transformations to the standard system can be obtained: $\sigma_v = 0.011$, $\sigma_{(b-y)} = 0.006$, $\sigma_{m_1} = 0.015$, $\sigma_{c_1} = 0.015$, $\sigma_{H_{\beta}} = 0.015$. The photometric precision in the instrumental system was: $\sigma_u = 0.017$, $\sigma_v = 0.013$, $\sigma_b = 0.011$, $\sigma_y = 0.009$.

The averaged standard magnitudes and indices for target and comparison stars are given in Table 1. The Strömgren indices for 7 Aql and comparison stars are reported for the first time in the present paper. Whereas, a number of photometric indices $[(b - y), m_1, c_1, H_{\beta}]$ are available for 8 Aql. In particular, Crawford (1975) gives (0.178, 0.178, 0.834, 2.747), Gronbeck & Olsen (1976, 1977) list (0.176, 0.183, 0.831, 2.752) and Hauck & Mermilliod (1976) give (0.177, 0.181, 0.832, 2.749). These are in agreement with those reported in Table 1 within 1- σ error.

2.2. Spectroscopic observations

Spectroscopic observations were conducted at the 2.12-m telescope of the same observatory during July 24, 2008 (UT). We used the Boller & Chivens spectrograph installed in the Cassegrain focus of the telescope. The 600 lines/mm grating was used to cover a wavelength range from 3900 to 6000 Å. A dispersion of 2.05 Å per pixels with a resolution of 5.6 Å was employed. The SITE3 1024 × 1024 pixel CCD with a 0.24 μm pixel size was attached to the spectrograph. Fig. 1 displays examples of the spectra, which were reduced in the standard way using the IRAF package. A comparison of the normalized spectra with those of well classified stars available in the literature was carried out. The spectrum of 8 Aql is very similar to that of HD 89254 (F2III) of the library of stellar spectra STELIB (Le Borgne et al., 2003). On the other hand, the spectrum of the star HD 90277 (F0V) of the same library reproduces our spectra of 7 Aql fairly well, besides that its resolution is twice as high as our.

3. Physical parameters

We have used the standard indices $uvby - \beta$ listed in Table 1 to estimate the reddening as well as the unreddened colours of our target stars. The calibrations of Nissen (1988) which are based on calibrations of Crawford (1975, 1966, 1979) for A- and F- type stars were implemented. The derived physical parameters are listed in Table 2. The confidence of the physical parameters can be assessed by comparing the distances derived in the present study with those estimated from accurate trigonometric parallaxes. In particular, the HIPPARCOS parallax measurement for 7 Aql is 7.70 ± 0.80 mas and for 8 Aql is

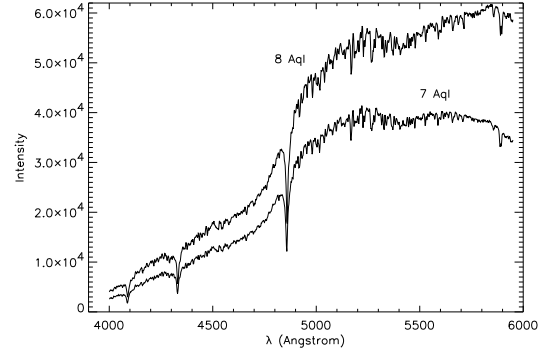


Figure 1: Low resolution spectra of target stars 8 Aql and 7 Aql.

11.80 ± 0.78 mas. The corresponding distances are 130 ± 15 pc and 85 ± 6 pc respectively. Thus, there is a good agreement between trigonometric and photometric distances. The T_{eff} , $\log g$ and metallicity from observed colours have been determined by means of the code TempLogG (Rogers, 1995; Kupka & Bruntt, 2001). The resulting physical parameters are listed in Table 3. The spectral types and luminosity classes of the stars can be determined through the relationship between MK spectral types and the reddening free indices β , $[m_1] = m_1 + 0.18(b - y)$, $[c_1] = c_1 - 0.20(b - y)$ by Oblak et al. (1975). Considering the indices listed in Table 1 with the errors, we have found a spectral classification for the target stars between A9 and F2, with luminosity class of either III or V. Therefore, no unique spectral type can be obtained from Strömgren photometry. This is due to the fact that the Strömgren standard indices used to assign a determined MK type in Oblak et al. (1975) have a rather high standard deviation, hence more than one MK type could be assigned to the target stars.

4. Differential light curves and frequency analysis

Figure 2 displays examples of the differential light curves in the y Strömgren filter of the target stars for three selected nights (vertical panels). The last three horizontal panels, from left to right, correspond to the differential light curve HD 174046 - HD 174625.

A period analysis has been performed by means of standard Fourier analysis and least-squares fitting. In particular, the amplitude spectra of the differential time series were obtained by means of an iterative sinus wave fit (ISWF; Ponman 1981).

The amplitude spectra of the differential v light curves 7 Aql-c2, 8 Aql-c2 are shown in the top panels of each plot of Figure 3(a). The subsequent panels of each plot in the figure, from top to bottom, illustrate the process of detection of the frequency peaks in each amplitude spectrum. We followed the same procedure as explained in Álvarez et al. (1998) and employed by Fox Machado et al. (2000, 2002a,b, 2008b). We have used a threshold of 3.7- σ above the mean noise level of the 100 μHz closest to the peak in the amplitude spectrum to consider a frequency as statistically significant, as described in Álvarez et al. (1998).

Table 1: Averaged standard magnitudes and indices for target and comparison stars. The number of $uvby$ and H_β measurements are indicated as N_{uvby} and N_β respective.

Star	V (mag)	$(b - y)$ (mag)	m_1 (mag)	c_1 (mag)	H_β (mag)	N_{uvby}/N_β
7 Aql	6.894	0.171	0.180	0.873	2.755	291/26
8 Aql	6.075	0.178	0.185	0.822	2.730	288/26
HD 174046 (c1)	9.570	0.276	0.078	1.097	2.867	285/26
HD 174625 (c2)	9.436	0.363	0.101	0.553	2.664	292/26

Table 2: Physical parameters for the target stars derived from Nissen's (1988) calibrations.

Star	$E(b - y)$ (mag)	$(b - y)_0$ (mag)	m_0 (mag)	c_0 (mag)	β_0 (mag)	m_V (mag)	M_V (mag)	Distance (pc)
7 Aql	0.000	0.173	0.180	0.873	2.755	6.89	1.25	134
8 Aql	0.000	0.196	0.185	0.822	2.730	6.07	1.27	92

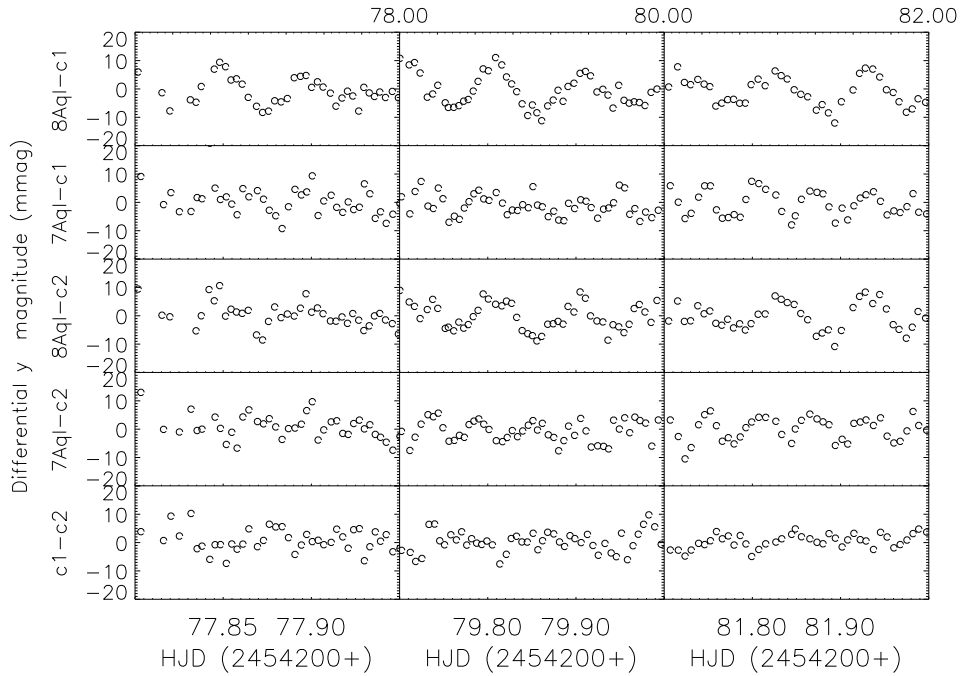


Figure 2: Examples of the differential light curves taken with the Strömgren spectrophotometer using the y filter with reference star HD 174046 = c1 and HD 174625 = c2. The name of each one differential light curve is indicated at left.

The window function of the observations is shown in 3(b). The resolution measured from the FWHM of the main lobe in the spectral window is $\Delta\nu = 1.1 \mu\text{Hz}$. The results obtained from the prewhitening process of the Strömgren vby time series are listed in Table 4, where the detected frequencies with their corresponding amplitudes and phases are given. The data from the Strömgren u band are omitted hereafter for sake of clarity. The formal errors derived from non-weighting fits are also listed. We note that for uncorrelated observations like ours these uncertainties usually may underestimate the real errors in amplitudes and phases.

The detected frequencies in the Strömgren v band ($\lambda = 4110 \text{ \AA}$, $\Delta\lambda = 170 \text{ \AA}$) can be compared with those reported by Fox Machado et al. (2007) whose observations were obtained through a similar interferometric blue filter ($\lambda \approx 4200 \text{ \AA}$, $\Delta\lambda \approx 190 \text{ \AA}$). Nonetheless, the time series analyzed by Fox Machado et al. (2007) are based on a multisite campaign and therefore the final resolution is better. They detected three frequency peaks in 8 Aql namely $108.04 \mu\text{Hz}$ (4.1 mmag), $110.20 \mu\text{Hz}$ (6.1 mmag), $143.36 \mu\text{Hz}$ (9.6 mmag). As can be seen in Table 4 we have detected the same frequencies in this season, but with smaller oscillation amplitudes. We note, how-

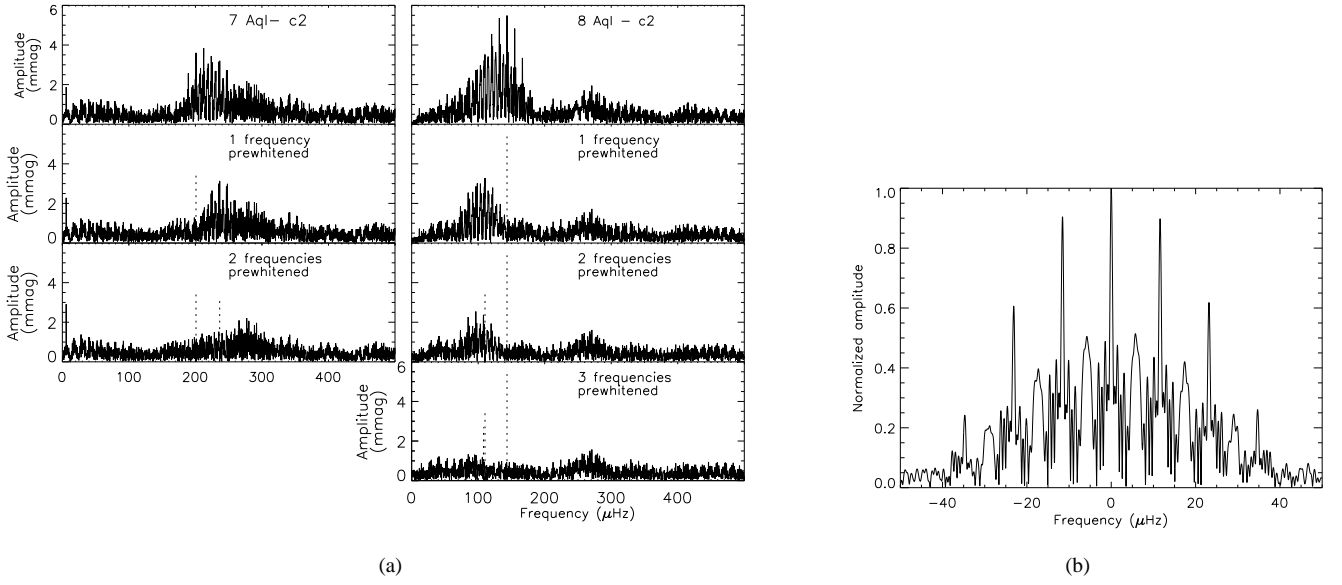


Figure 3: (a) Pre-whitening process in the spectra derived from the PP ν differential light curves 7 Aql-c2 (left) and 8 Aql-c2 (right). (b) Spectral windows in amplitude

ever, that the amplitude ratio A_{ν_1}/A_{ν_2} and A_{ν_1}/A_{ν_3} are almost the same in both studies. In particular, the amplitude of the dominant mode, ν_3 , is 1.8 times smaller in our one-site observations. Even though, the oscillation amplitudes are big enough to be detected in our run.

Regarding 7 Aql Fox Machado et al. (2007) detected six significant frequency peaks namely $193.28 \mu\text{Hz}$ (2.8 mmag), $201.05 \mu\text{Hz}$ (3.8 mmag), $222.08 \mu\text{Hz}$ (3.6 mmag), $223.96 \mu\text{Hz}$ (3.4 mmag), $236.44 \mu\text{Hz}$ (6.1 mmag), $295.78 \mu\text{Hz}$ (1.5 mmag). Among these we have confirmed only two frequency peaks. ν_1 most likely corresponds to $201.05 \mu\text{Hz}$ of Fox Machado et al. (2007) with similar amplitude, while ν_2 beyond no doubt is the dominant mode $236.44 \mu\text{Hz}$ with smaller oscillation amplitude. From the amplitude ratio of the detected modes in Fox Machado et al. (2007) a smaller amplitude is expected for $\nu_1 \sim 201 \mu\text{Hz}$. Therefore, the amplitude of this peak probably was affected by the side lobes. We think that the difference in amplitude of the modes in both seasons is a consequence of the bad coverage rather than intrinsic amplitude variability. In fact, if we define the oscillation amplitude (A_{osc}) as the maximum constructive interference of the observed modes a short time series might induce an underestimation of the amplitude especially in presence of beating phenomena due to close frequencies. As shown by Fox Machado et al. (2007) the oscillation amplitudes of the modes in 8 Aql are on average 1.9 times larger than those of 7 Aql. This explains the fact that we have only detected two oscillation modes in 7 Aql, but all in 8 Aql.

5. Preliminary comparison with theoretical models

In this section the pulsation constants will be computed in order to try to disentangle possible radial modes. Then the fre-

Table 4: Frequency peaks detected in the light curves 7 Aql - c2 and 8 Aql - c2. S/N is the signal-to-noise ratio in amplitude after the prewhitening process. The origin of φ is at 24544272.72047

ν	Freq. (μHz)	A (mmag)	φ (rad)	S/N
7 Aql				
Filter ν				
ν_1	200.90 ± 0.05	3.64 ± 0.3	-0.53 ± 0.03	5.9
ν_2	236.53 ± 0.05	3.22 ± 0.3	$+0.10 \pm 0.03$	4.2
Filter b				
ν_1	200.91 ± 0.04	3.38 ± 0.3	-0.57 ± 0.03	6.1
ν_2	236.55 ± 0.06	2.48 ± 0.3	$+0.06 \pm 0.04$	3.8
Filter y				
ν_1	200.89 ± 0.05	2.64 ± 0.3	-0.50 ± 0.03	5.6
ν_2	236.54 ± 0.06	2.22 ± 0.3	$+0.23 \pm 0.04$	4.2
8 Aql				
Filter ν				
ν_1	143.38 ± 0.04	5.38 ± 0.3	-2.54 ± 0.02	11.5
ν_2	110.24 ± 0.05	3.56 ± 0.3	-0.67 ± 0.03	6.7
ν_3	107.99 ± 0.06	2.69 ± 0.3	$+2.48 \pm 0.04$	5.1
Filter b				
ν_1	143.37 ± 0.04	4.92 ± 0.3	-2.42 ± 0.02	13.3
ν_2	110.26 ± 0.04	2.86 ± 0.3	-0.74 ± 0.03	7.0
ν_3	107.96 ± 0.06	2.33 ± 0.3	$+2.59 \pm 0.04$	5.7
Filter y				
ν_1	143.36 ± 0.03	3.98 ± 0.3	-2.32 ± 0.03	10.8
ν_2	110.23 ± 0.04	1.80 ± 0.3	-0.44 ± 0.05	4.3
ν_3	107.92 ± 0.05	1.49 ± 0.3	$+2.91 \pm 0.06$	3.6

quencies listed in Table 4 will be used in an attempt of multi-colour mode identification. A more complete modelling con-

Table 3: Fundamental parameters for the target stars computed with the TempLogG code.

Star	M_V (mag)	D (pc)	T_{eff} (K)	$\log g$	[Fe/H]
7 Aql	1.22	136	7257	3.62	0.01
8 Aql	1.23	92	7051	3.51	0.14

sidering the frequency modes detected by Fox Machado et al. (2007) will be given in a forthcoming paper.

Figure 4 shows the de-reddened position of the target stars in an T_{eff} -magnitude diagram. The computation of the theoretical evolutive sequences are explained in Fox Machado et al. (2006). The observed absolute magnitudes M_V were taken from Table 2, while the T_{eff} are from Table 3. Error bars of 0.1 mag for M_V and 100 K for T_{eff} have been adopted. The dotted lines are evolutive sequences of non-rotating models without overshooting giving a range of masses suitable for 7 Aql. The dashed line corresponds to an evolutive track of models of $2.20 M_{\odot}$ which match approximately the observational position of 8 Aql. We have used a chemical initial composition of [Fe/H] = 0.066 for 7 Aql and [Fe/H] = 0.148 for 8 Aql. According to the models depicted in Fig. 4 the mass of 8 Aql is $0.2 M_{\odot}$ larger than that of 7 Aql. Their ages should be between 800 and 1000 Myr. We note that the effect of rotation have been neglected. However as shown by Pérez Hernández, et al. (1999) the effect of rotation is important not only in the location of the stars in a colour-magnitude diagram but also on the pulsation modes even for low rotators like 7 Aql ($v \sin i = 32$ km/s).

The pulsation constant Q is expressed in terms of four observable parameters as follows (Breger, 1990):

$$\log Q = -6.456 + \log P + 0.5 \log g + 0.1 M_{\text{bol}} + \log T_{\text{eff}} \quad (1)$$

Using the parameters listed in Table 3 and considering the bolometric corrections for the target stars (Balona, 1994), we find for 7 Aql $Q_{\nu_1} = 0.0127$ and $Q_{\nu_2} = 0.0108$. For 8 Aql we have $Q_{\nu_1} = 0.0153$, $Q_{\nu_2} = 0.0199$ and $Q_{\nu_3} = 0.0203$. Comparing these Q -values with the theoretical ones (2.0M48 model by Fitch, 1981) we find that the oscillation modes ν_1 and ν_2 of 7 Aql are indicative of p modes of either $l = 0, 2$ or 3 with overtones $n = 5$ and $n = 7$, respectively.

On the other hand, the 2.0M49 model (Fitch, 1981), which match approximately the parameters of 8 Aql yields either identifications ($l = 1, n = 4$) or ($l = 2, n = 4$) for ν_1 , while the frequencies ν_2 and ν_3 are consistent with either radial pulsations ($l = 0, n = 2$) or non-radial oscillations ($l = 2, n = 2$).

5.1. Multicolour photometry

It is well known that the amplitude and phases observed with the Strömgren filters can be used to estimate the spherical degree l of the mode (Watson, 1988; Garrido et al., 1990). This estimation is done comparing the observed amplitude ratios and phase differences with theoretical predictions.

One equilibrium model per star has been obtained, passing by the center of the observed photometric error box. The numerical code CESAM (Morel, 1997) is used to obtain these models, fixing standard physics for δ Scuti stars (see Casas et al., 2009).

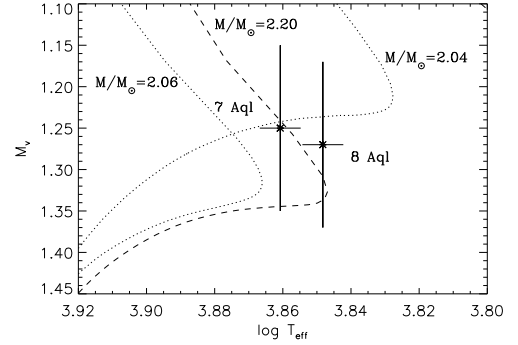


Figure 4: HR diagram showing the location of the target stars. The slightly cooler star is 8 Aql. Evolutive sequences of non-rotating models without overshooting are shown by dotted ([Fe/H] = 0.066) and dashed lines ([Fe/H] = 0.148). The error bars give the position of the stars according to the uncertainties discussed in Sect 3.

The non-adiabatic pulsational code GraCo (Moya et al., 2004; Moya & Garrido, 2008) has also been used for obtaining the variation of the flux and the phase-lags necessary to compute the variation of the magnitude as a function of the wave length. As both stars are close to the red edge of the δ Scuti's instability strip, the outer convection zone is well developed. Therefore, the equations describing the convection-pulsation interaction are required. To do so, the Time Dependent Convection (Grigahcène et al., 2005) has been used in GraCo.

Examples of the final comparison between observations and theoretical predictions are depicted in Fig. 5. The horizontal axe shows the phase difference in gradus, while the vertical one the amplitude ratios.

Unfortunately, with the large error bars derived for the present sparse observations, in some cases the oscillations are compatible with all possible non-radial and radial modes up to $l = 3$. In others, the discrimination is not good. Even so, most identifications point towards the presence of degrees with $l \geq 2$ values. If that hypothesis were correct the presence of radial oscillations derived from Fitch's models could be excluded. Therefore, the two detected frequencies in 7 Aql could be identified as $l = 2$ and $n = 5, 7$; while the three frequencies in 8 Aql would be consistent with $l = 2$ and $n = 4, 2, 3$. However, continuous multicolour time series are required for a more conclusive study.

6. Conclusions

We have presented the results obtained in an one-site observational photometric campaign on the δ Scuti stars 7 Aql and 8 Aql. Photoelectric photometric $uvby - \beta$ data were acquired at

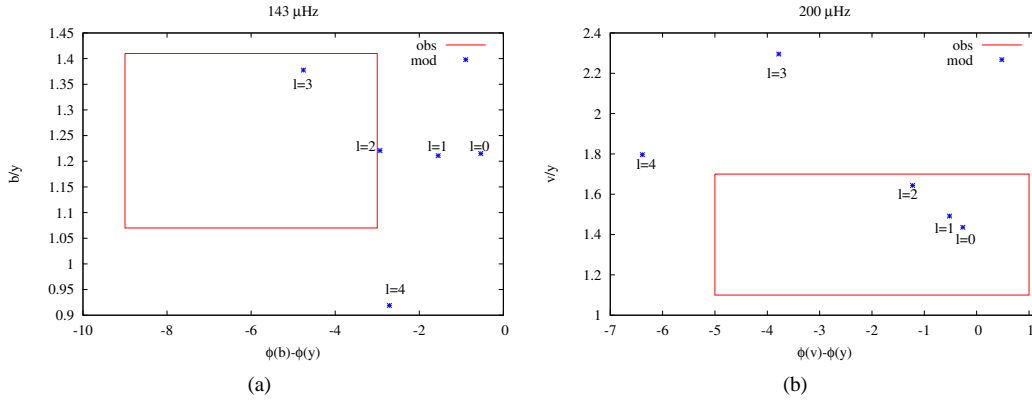


Figure 5: Phase-amplitude diagram for the Strömgren filters showing the comparison between observed difference phase-amplitude ratio (boxes) and theoretical predictions (asterisks). (a) b and y bands for the frequency $\nu_1 = 143.38 \mu\text{Hz}$ of 8 Aql. (b) v and y bands for the frequency $\nu_1 = 200.90 \mu\text{Hz}$ of 7 Aql.

the 1.5-m telescope of SPM observatory by using the Strömgren six channel spectrophotometer.

Strömgren standard indices for 7 Aql, 8 Aql and comparison stars are reported. The main physical parameters have been derived from the Strömgren photometry. These have been used to place the target stars in an T_{eff} -magnitude diagram. The star 8 Aql is about $0.2 M_{\odot}$ more massive than 7 Aql, while their absolute magnitudes are rather similar.

The pulsation constant Q has been computed for the modes detected in the present study. An attempt of mode identification by means multicolour photometry has been carried out. The stars seem to oscillate with modes of degree $l = 2$ or higher. However, longer multicolour time series are required for a more conclusive study. The analysis of few low resolution spectra points that 7 Aql and 8 Aql are stars of spectral type F0V and F2III respectively.

Acknowledgments

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